Indirect detection of Dark Matter with the ANTARES Neutrino Telescope

V. Bertin

INDIRECT DETECTION OF DARK MATTER WITH THE ANTARES NEUTRINO TELESCOPE

V. BERTIN, on behalf of the ANTARES Collaboration
CPPM, Aix-Marseille Université, CNRS/IN2P3,
163 avenue de Luminy – Case 902, 13288 Marseille cedex 9, France

Indirect search for Dark Matter trapped inside celestial bodies is one of the main physics goals of neutrino telescopes. The analysis performed with the data recorded by ANTARES in 2007 and 2008 to detect the flux of neutrinos originating from Dark Matter inside the Sun is reviewed. The obtained limits on the neutrino flux and on the WIMP-nucleon cross-sections are presented and compared to other existing limits from direct and indirect detection experiments as well as predictions from SUSY models such as the CMSSM and the more phenomenological MSSM-7 model.

1 Introduction

The most popular paradigm of modern cosmology considers the Dark Matter as a population of stable weakly interacting massive particles (WIMPs) relic from the Big Bang, although not yet discovered. Those particles would gravitationally accumulate in the core of massive celestial bodies such as stars or to a lesser extend planets, where they could self-annihilate into ordinary matter and eventually produce significant high energy neutrino fluxes. Indirect search for Dark Matter looking at such neutrino signals coming from the core of the Sun, the Earth or the Galactic Centre is thus one of the main physics goals of neutrino telescopes.

2 The ANTARES neutrino telescope

The ANTARES detector [1] is the first undersea neutrino telescope and the largest one of the Northern hemisphere. It is composed of 12 mooring lines, each holding 75 photomultipliers distributed on 25 storeys (the titanium structure holding a triplet of photodetectors), installed at a depth of about 2500 metres off shore of the Provençal coast of France, in order to form a 3D-matrix of ~900 photodetectors.The main goal of the experiment is to look for the Cherenkov light induced by high energy muons during their travel in the sea water throughout the detector. The trajectory of the muon track is reconstructed from the detection time of the Cherenkov photons as well as from the positions of the photodetectors. An indirect search for neutrinos can then be performed by selecting upward-going muons produced by neutrinos which have passed through the entire Earth and interacted in the vicinity of the detector. The direction of the incoming neutrino, being almost collinear with the secondary muon, can then be determined with an accuracy reaching 0.2° for high energy neutrinos above 10 TeV. Due to its size and the spacing of the photomultipliers, the ANTARES detector has a low energy threshold of ~20 GeV for reconstructed neutrinos and an effective area of $\sim 10^{-3}$ m^2 for neutrinos with an energy of 500 GeV. The effective area increases strongly with the neutrino energy and reaches ~1 m^2 for PeV energy neutrinos. Its location in the Northern hemisphere makes it complementary in sky coverage with the South Pole neutrino telescope IceCube. In addition, a large fraction of the full sky can be observed with ANTARES thanks to the rotation of the Earth, including the central part of the Galaxy which is believed to be the host of many high energy phenomena.

The building of the ANTARES detector started in 2006 with the installation and the operation of the first line, and was completed in May 2008. The analysis presented here is based on the data recorded in 2007 with a 5-line detector and in 2008 with a 9-to-12-line detector. The event reconstruction is performed by a χ^2 fit of the photodetector hit times as a function of their positions assuming that the light originates from the Cherenkov cone of a muon track passing though the detector [2]. Although the photomultipliers point at 45° downwards, the vast majority of reconstructed events are due to down-going atmospheric muons. The neutrino candidates are obtained by looking for upward-going tracks selected by a set of quality cuts on the reconstruction parameters in order to reject the background of badly reconstructed down-going atmospheric muons. After selection, the event sample contains about 1000 neutrino candidates recorded in $\sim$295 effective days of data taking.

3 Indirect search of Dark Matter annihilations in the Sun with ANTARES

A search for neutrinos produced by Dark Matter annihilations into the Sun has been carried out in the data sample collected by ANTARES in 2007 and 2008 [3]. The analysis is based on a binned search strategy looking for an excess of neutrino events in a cone centered towards the direction of the Sun over the background of atmospheric neutrinos. Although a good agreement in the number and the distribution of events between data and Monte Carlo simulation is observed after selection, the background coming from atmospheric muon and atmospheric neutrino events has been estimated directly from the data sample by scrambling the recorded time of the events in order to generate a fake Sun. This allows to suppress the systematic errors coming from the uncertainties on the fluxes of atmospheric muon and neutrino events.

The estimation of the neutrino signal induced by Dark Matter annihilations in the core of the Sun has been estimated by using the WIMPSIM package [4] which generates the neutrino spectrum originating from the annihilations in the model independent way. For a given neutrino mass, this Monte Carlo simulation program calculates the capture rate and the annihilation rate in the Sun at equilibrium and generates the neutrino spectrum resulting from all possible self-annihilation channels. The propagation of the neutrinos within the Sun and in vacuum up to the Earth is simulated taking into account neutrino interactions and regeneration of the tau leptons in the Sun medium, as well as neutrino oscillations in a full three-flavour framework.

The sensitivity to Dark Matter signal has been estimated in a model independent way by considering an extreme "soft" neutrino spectrum corresponding to self-annihilations into b-quarks and a "hard" neutrino spectrum corresponding to self-annihilations into W/Z boson pairs or tau leptons. These channels are well representative of a WIMP in the form of neutralinos in the framework of Minimal Supersymmetric extensions of the Standard Model (MSSM). A full sensitivity study has been performed for 17 different values of the WIMP mass ranging from 10 GeV to 10 TeV.

For a WIMP with a given mass and a given neutrino annihilation spectrum, the number of signal events is obtained by convoluting the neutrino flux with the detector efficiency, the so-called effective area, determined for a given set of the selection parameters, mainly the values of the track fit quality parameter and of the half-opening angle of the search cone around the Sun. The sensitivity to a given WIMP model is thus derived as the ratio between the average upper limit on the number of background events estimated from the scrambled data, considering a Poisson statistics in the Feldman-Cousins approach [5], and the number of signal events predicted for the corresponding WIMP mass and annihilation spectrum, and for the lifetime of the data taking. Following the Model Rejection Factor (MRF) technique [6], the values of the cuts on the track fit quality parameter and on the half-cone opening angle are optimized for each considered

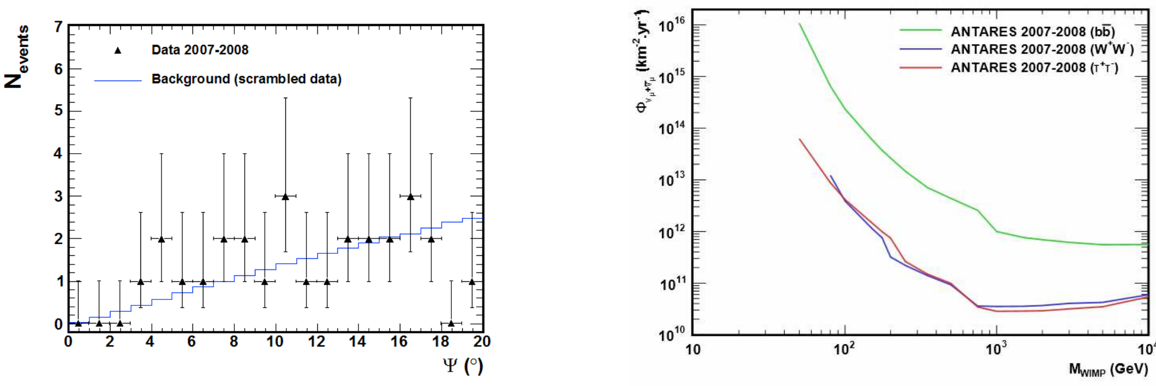

Figure 1: Left: Observed number of events in the data collected by ANTARES in 2007-2008 as a function of the angular separation between the direction of the event track and the Sun position compared to the background distribution estimated from scrambled data. Right: Upper limits on the muon neutrino plus anti-neutrino flux coming from the Sun as a function of the WIMP mass obtained by ANTARES for the considered self-annihilation channels.

model in order to minimize the sensitivity. The optimization leads to a selection cone around the Sun of $3° - 5°$ of half-opening angle for the various models corresponding to about 1-3 events of background inside the cone.

4 Results and perspectives

Figure 1 (left) shows the differential distribution of the observed number of selected events in the data recorded by ANTARES in 2007-2008 as a function of the angular separation between the direction of the event track and the position of the Sun at the time of the event. As illustrated, no excess in the direction of the Sun has been observed with respect to the distribution of the expected background due to atmospheric neutrino and atmospheric muon events estimated from scrambled data. This allowed to derive upper limits on the flux of muon neutrino plus anti-neutrino flux coming from the Sun and resulting from self-annihilations of Dark Matter particles in the core of the Sun [3]. Figure 1 (right) show such limits as a function of the WIMP mass for the considered "soft" and "hard" annihilation channels assuming a 100% branching ratio in that channel. Given its soft energy spectrum, the channel $b\bar{b}$ yields the weakest limit, while the others $(W^+W^-, \tau^+\tau^-)$ are the most stringent.

This neutrino flux, related to the annihilation rate of Dark Matter into the Sun, can also be related to the capture rate of the WIMPs by elastic scattering, and thus to the scattering cross-sections of the WIMPs on protons, with the reasonable hypothesis of equilibrium between the WIMP capture and self-annihilation rates in the Sun. Figure 2 presents the corresponding upper limits on the spin-dependent (SD) and spin-independent (SI) WIMP-proton cross-sections as a function of the WIMP mass, which can be derived from the limits on the neutrino flux coming from the Sun obtained by ANTARES. Individual limits on the SD and SI components of the cross-sections are derived assuming that one or the other is dominant. The latest and most stringent limits from other indirect and direct detection experiments are also shown. The predictions of the phenomenological MSSM-7 model, obtained with an adaptative grid scan of its parameter space performed with the DarkSUSY program [7] and taking into account the latest constraints for various observables from accelerator-based experiments and in particular the recent measurement of the Higgs boson mass, are also presented for comparison. A similar analysis of the parameter space of the more constraint CMSSM has also been performed and compared to our limits [3]. These analyses demonstrates the complementarity as well as the great sensitivity of neutrino telescopes with respect to direct detection experiments in the hunting quest for the Dark Matter of the Universe. In particular, ANTARES and IceCube are now

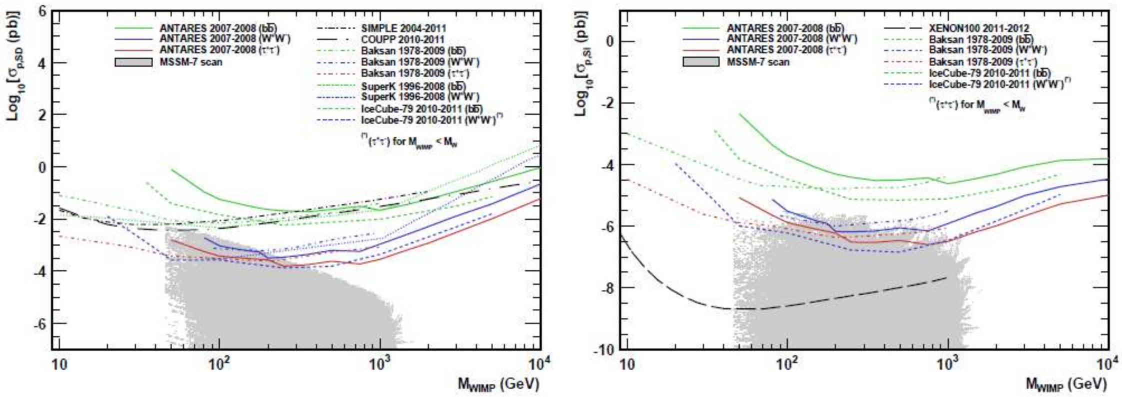

Figure 2: Upper limits on the spin-dependent (left) and spin-independent (right) WIMP-proton cross sections as a function of the WIMP mass obtained by ANTARES for the considered self-annihilation channels, compared to the results of other indirect and direct search experiments. The predictions of a grid scan of the MSSM-7 model are also presented for comparison.

starting to probe interesting regions of the parameter space of SUSY models.

Thanks to the data taking performed since 2008 with a complete detector, ANTARES has now accumulated more than 7000 neutrinos corresponding to about seven times the statistics used in the analysis presented here. In addition, studies are being performed to further improve the sensitivity of such analysis by using an energy estimator in order to obtain a better selection of the Dark Matter neutrino signal events with respect to the atmospheric neutrino background, or by using alternative event reconstruction algorithms with better performances for low energy events. Another improvement comes from the inclusion in the analysis of the events reconstructed on a single detector line which were rejected by the standard analysis presented above in a first place, since the azimuth angle of the reconstructed track cannot be determined for such events. A similar analysis can anyway be followed by constraining the zenith angle of the track to be close to the one of the Sun while integrating over the whole azimuth band. A major improvement of the analysis sensitivity is then observed for low mass WIMPs ($M_{WIMP} < 120$ GeV) for which low energy neutrino events reconstructed on a single detector line are dominant. Preliminary studies of this improved analysis looking for neutrino produced by annihilation of Dark Matter inside the Sun performed on the ANTARES data set collected between 2007 and 2010 show an improvement of almost a factor 10 on the sensitivity to the WIMP-proton cross-sections with respect to the present limits of ANTARES. In addition, other potential Dark Matter sources such as the Earth, the Galactic Centre and Dwarf Spheroidal galaxies are being studied in the Collaboration by dedicated analyses. The hunt for Dark Matter with ANTARES is therefore only starting and the near future will certainly be exciting.

References

1. M. Ageron et al., ANTARES Collaboration, *Nucl. Instrum. Methods* A **656**, 11 (2011).
2. J.A. Aguilar et al., ANTARES Collaboration, *Astropart. Phys.* **34**, 652 (2011).
3. S. Adrian-Martinez et al., ANTARES Collaboration, [arXiv:1302.6516], submitted to JCAP.
4. M. Blennow, J. Edsjo, T. Ohlsson, *JCAP* **0801**, 021 (2008).
5. G.L. Feldman and R.D. Cousins, *Phys. Rev.* D **57**, 3873 (2003).
6. G.H. Hill and K. Rawlins, *Astropart. Phys.* **19**, 393 (2003).
7. P. Gondolo et al., *J. Cosm. and Astropart. Phys.*, JCAP07, 008 (2004).